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Management of Respiratory Failure in Hemorrhagic Shock

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Abstract

Hemorrhagic shock results in acute respiratory failure due to respiratory muscle fatigue and inadequate pulmonary blood flow. Because positive pressure ventilation can reduce venous return and cardiac output, clinicians should use the minimum possible mean airway pressure during assisted or mechanical ventilation, particularly during episodes of severe hypovolemia. Hypoperfusion also worsens dead space fraction. Therefore, clinicians should monitor capnography during mechanical ventilation and recognize that hypercapnia may be treated with fluid resuscitation rather than increasing minute ventilation.

Keywords: mechanical ventilation; hemorrhagic shock; respiratory failure

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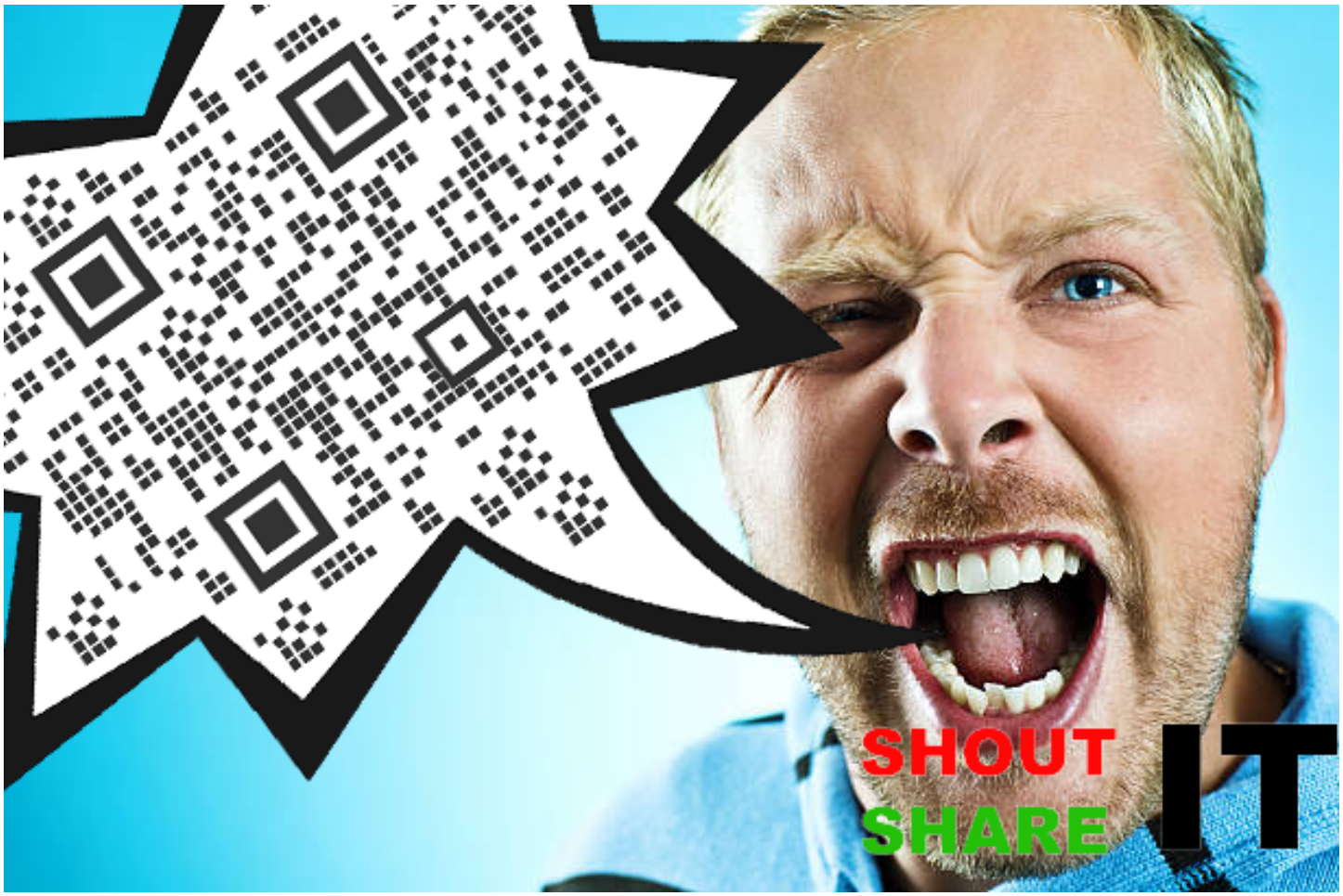
Respiratory failure due to hemorrhagic shock is a common, yet underappreciated, clinical syndrome. Certain features of this syndrome make it a distinct pathophysiologic entity that differs from respiratory failure from other forms of shock. First, the reduced red blood cell mass causes greater reductions in O_2 delivery than in simple hypovolemia. Second, hypovolemia from hemorrhage tends to be dynamic, because of episodic bleeding and the effects of resuscitation. Third, hemorrhage magnifies the deleterious effects of positive pressure ventilation compared with cardiogenic or vasodilatory shock. The management of respiratory failure in hemorrhagic shock is difficult because patients often require positive pressure ventilation, which may cause catastrophic hemodynamic collapse (1, 2). Unfortunately, there is little evidence from clinical trials to guide care in this syndrome. Therefore, we propose a management strategy that is based on physiologic principles.

Pathophysiology of Respiratory Failure during Hemorrhagic Shock

Hemorrhagic shock can cause respiratory failure by reducing perfusion of the neuromuscular system. Severe hemorrhage reduces diaphragmatic blood flow, which can fatigue and weaken the contractile force of the diaphragm (3, 4). Moreover, hypoperfusion of the brain can cause obtundation, which depresses airway reflexes and relaxes the muscles that normally dilate the pharynx. Relaxation of pharyngeal muscles can narrow and obstruct the upper airway, especially if the neck is flexed or in the neutral position (4–7). In addition, a severe reduction in blood flow to the brain causes tachypnea and deep inspiratory gasps (8). When hypoperfusion of the brain exceeds a critical threshold, respirations slow, then become erratic, and ultimately cease (7, 9, 10). Apnea usually precedes circulatory arrest during progressive shock (9, 10).

Severe hemorrhage has important effects on the partial pressure of CO_2 in systemic arterial blood (Pa_{CO_2}). Tachypnea and respiratory alkalosis are common in mild and moderate bleeding (11). However, patients with hemorrhagic shock will often have a normal or elevated arterial Pa_{CO_2}, despite tachypnea (11–13). Hemorrhagic shock reduces the exhalation of CO_2 by reducing the cardiac output and the rate at which pulmonary blood flow delivers CO_2 to alveoli. As a result, the partial pressure of CO_2 in alveolar air is lower than the normal value of 40 mm Hg (13) (Figure 1). Clinicians can monitor the partial pressure of CO_2 in the alveoli with the end-tidal CO_2 displayed by capnography. Severe blood loss will decrease the end-tidal CO_2. For example, an end-tidal CO_2 of 25 mm Hg in a patient intubated for trauma suggests severe shock and predicts the need for massive transfusion (14). The combination of low end-tidal CO_2 and elevated Pa_{CO_2} is due to an increased proportion of dead space ventilation (15, 16).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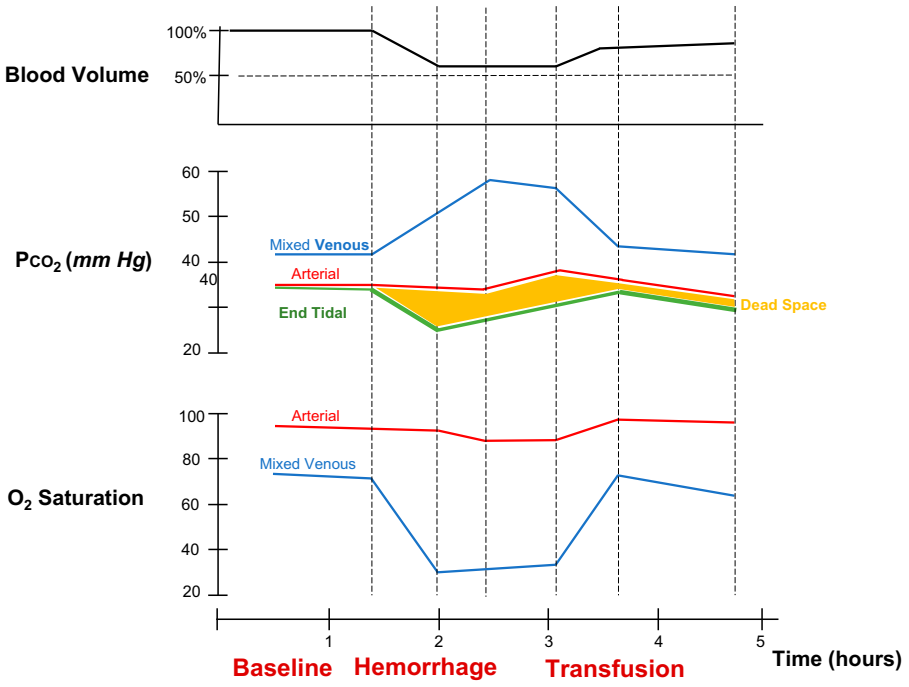

Figure 1. Effect of acute severe blood loss on O_2 and CO_2 tensions in canine model. The end-tidal CO_2 decreases and arterial Pco_2 increases during severe hypovolemia, which normalizes with transfusion. Adapted by permission from Gerst and colleagues (13). CO_2 = carbon dioxide; O_2 = oxygen; Pco_2 = carbon dioxide partial pressure.

Normally, the Pa_{CO_2} is no more than 5 mm Hg greater than end-tidal CO_2 (17). In hemorrhagic shock, a Pa_{CO_2} that is 10 mm Hg greater than end-tidal CO_2 predicts death (12). In hemorrhage, low cardiac output, rather than anemia, increases dead space ventilation (18). Table 1 shows the effect of hemorrhagic shock on arterial and end-tidal CO_2. When hemorrhage increases dead space ventilation, increasing respiratory rate and tidal volume do not effectively lower arterial Pa_{CO_2} (16). Therefore, hemorrhagic shock leads to a vicious cycle in spontaneously breathing patients: rising blood Pa_{CO_2} stimulates ineffective hyperventilation, which increases metabolic production of CO_2 from the work of breathing. As hemorrhagic shock progresses toward death, the inadequate perfusion extinguishes tissue metabolism and slows CO_2 production. Therefore, end-stage hemorrhage accelerates the decline in end-tidal CO_2 (19).

Hypercapnia impairs the respiratory compensation for shock-induced metabolic acidosis (11). The result is acidemia, which can worsen coagulopathy and lead to systemic vasodilation and pulmonary vasoconstriction (20–22). Hypercapnia may also decrease myocardial and diaphragmatic contractility (20, 23, 24). The negative effects of acidemia may be partially offset by increased offloading of O_2 to the tissues by the Bohr effect (25).

Severe hemorrhage decreases the oxygen saturation of hemoglobin in mixed venous blood flowing in the pulmonary artery (Figure 1). This decrease occurs because peripheral tissues attempt to extract the O_2 they require for metabolism despite anemia and reduced cardiac output. In other words, mixed venous oxygen saturation decreases when blood loss reduces O_2 delivery into the systemic capillaries. The decrease in mixed venous O_2 saturation is an early sign of severe hemorrhage (11, 13). However, the detection of low mixed venous oxygen requires a pulmonary artery catheter and is not specific for hemorrhage.

Although severe hemorrhage reliably reduces the oxygen saturation of mixed venous blood, it has a variable effect on the oxygen saturation of systemic arterial blood (Table 1). Pulse oximetry appears to be a reliable measurement of oxygen saturation in healthy subjects with severe hypovolemia (26). Normal lungs can reoxygenate severely hypoxemic mixed venous blood. Therefore, during significant hemorrhage, the partial pressure of systemic arterial O_2 (Pa_{O_2}) is often unchanged or decreases mildly (11, 13, 16). Shunt physiology occurs when mixed venous blood returns to the left atrium without passing through the capillaries of ventilated alveoli, such as normal blood flow through the bronchial circulation. Severe hemorrhage may improve Pa_{O_2} by reducing the absolute volume of blood entering right-to-left shunts (16). This may be observed as hemorrhage reduces the cardiac output flowing into both normal and pathologic right-to-left shunts, reducing the mixture of hypoxic blood into systemic arterial blood (16). These factors tend to prevent a decrease in the Pa_{O_2}. However, the Pa_{O_2} may decrease during severe hemorrhage if the lung parenchyma is very abnormal. In this situation, the abnormal lungs may not be able to adequately oxygenate the severely hypoxemic blood flowing from the pulmonary arteries.

Severe hemorrhage also reduces the production of pulmonary surfactant, which reduces pulmonary compliance and leads to atelectasis (27). In addition to increased shunting of blood, atelectasis and reduced

Table 1. Summary of the effect of hemorrhagic shock on respiratory parameters

Parameter	Severe Hemorrhagic Shock
Dead space fraction	Increased
Respiratory rate	Elevated Slower and erratic when cardiac arrest imminent
Mixed venous oxygen saturation of hemoglobin	Low
Partial pressure of O_2 in arterial blood	Variable
Partial pressure of CO_2 in arterial blood	Normal to elevated
End-tidal CO_2	Low

Definition of abbreviations: CO_2 = carbon dioxide; O_2 = oxygen.

compliance as a result of hemorrhage can increase the load on underperfused muscles of respiration and contribute to hypoxemia (4, 28). Notably, pulmonary compliance remains abnormal after restoration of normal circulating blood volume (27). Complications of resuscitation, such as transfusion-associated circulatory overload and transfusion-associated lung injury, can also contribute to respiratory failure. These processes are more common in later stages of prolonged shock.

The net result of hemorrhagic shock is a failing respiratory pump, increased dead space fraction, reduced mixed venous oxygen tension, and a stiffer respiratory system. As a result, patients may require positive pressure ventilation, which can provide increased fraction of inspired oxygen, minute ventilation, and lung recruitment (29, 30).

Consequences of Positive Pressure Ventilation

The muscles of inspiration create negative intrathoracic pressure, which increases venous return to the heart (31). Conversely, positive pressure ventilation increases intrathoracic pressure, which decreases venous return and cardiac output. Hypovolemia greatly magnifies these hemodynamic effects (32, 33). Any pattern of positive pressure ventilation that increases mean airway pressure will decrease venous return. Therefore, large tidal volume, high plateau pressure, and frequent respiration can reduce cardiac output in hypovolemic patients. Clinicians may inadvertently cause hyperinflation during mask bag ventilation (34). The addition of positive end-expiratory pressure (PEEP) dramatically reduces venous return during hemorrhage. In preclinical models of hemorrhagic shock, even PEEP equal to 5 cm H_2O is fatal (32, 33, 35, 36). The effects of PEEP on venous return are complex and include dynamic compression of the venae cavae, as well as right atrial pressure and compliance (37).

The additive effects of positive pressure ventilation and sedatives contribute to hemodynamic collapse after endotracheal intubation of hypovolemic patients (1). Sedatives and opiates blunt the adrenergic response to hypovolemia and cause vasodilation. Some agents also depress cardiac function (38, 39).

A Physiologic Approach to Managing Respiratory Failure from Hemorrhagic Shock

Airway

Clinicians should first guarantee that patients have a patent airway. If the patient is unconscious, tilting the head (neck extension), thrusting the mandible anteriorly, and opening the mouth can relieve dynamic pharyngeal obstruction (5, 40). Nasopharyngeal and oral airways can be used if the initial steps are ineffective. Clinicians should monitor the oxygen saturation of hemoglobin with continuous pulse oximetry, which is accurate even in states of severe hypovolemia (26). Supplemental oxygen should be provided for hypoxemia (40). Preoxygenation should begin if endotracheal intubation is planned. If the patient has ineffective respiratory effort, clinicians can provide rescue breaths via bag-mask ventilation (5, 40, 41). As a general rule, the lowest mean airway pressure that is needed to ensure adequate minute ventilation should be used. Unless there is a specific need for lung recruitment, the lowest degree should be set on a PEEP valve during bag-mask ventilation, and the operator should give sufficient time for complete exhalation (36). The tidal volume should be just enough to allow the chest wall to rise. If there is severe hypovolemia but no imminent risk of respiratory arrest, bag-mask ventilation and endotracheal intubation should be delayed to allow initial volume resuscitation (40, 41). In this situation, a clinician should carefully monitor the patient's hemodynamics, respiratory drive, mental status, and gas exchange. Rescue breathing and endotracheal intubation should be performed immediately if there is ineffective ventilation or airway obstruction (40, 41).

The above strategy is consistent with the airway-breathing-circulation approach. The strategy also agrees with the "circulation first" approach, which is increasingly advocated for traumatic hemorrhage. This approach defers endotracheal intubation, when possible, in favor of basic noninvasive maneuvers to open the airway and provide the lowest possible amount of positive pressure ventilation support until severe hypovolemia is corrected (40). Importantly, resuscitation, control of hemorrhage, and airway management should be performed in parallel (41). This is especially crucial if early endotracheal intubation is necessary.

Support during Endotracheal Intubation

Clinicians should monitor systemic blood pressure frequently (such as every minute) or continuously by arterial catheterization when performing endotracheal intubation in patients with severe hemorrhage. Resuscitation with blood products and balanced crystalloid can improve venous return and cardiac output. However, clinicians must avoid excessive fluid resuscitation, especially before definitive control of bleeding (42). Similarly, vasopressors can increase venous return by venoconstriction and help maintain cerebral and coronary perfusion pressure (32, 39). Norepinephrine has been found to increase venous return by shifting blood from the splanchnic to systemic circulation (43). Animal models also support the use of norepinephrine, which may reduce the amount of fluid resuscitation required without impacting survival (42, 44). However, patients with severe blood loss typically have elevated endogenous catecholamines and systemic vascular resistance. Therefore, clinicians should use vasopressors for life-threatening hypotension, even while resuscitation is actively in progress (42). During induction of anesthesia for endotracheal intubation, clinicians can bolus or infuse vasopressors to prevent or treat hemodynamic collapse (41). Vasopressors should be immediately available during endotracheal intubation of patients with severe hemorrhage and can be administered through intraosseous, peripheral, and central venous catheters (39, 41, 45). The principles of damage control fluid resuscitation for hemorrhagic shock have been reviewed elsewhere (42, 46).

Patients with hemorrhagic shock often develop pulseless electrical activity in the minutes after successful endotracheal intubation (1, 2). Because sedation and neuromuscular blockade can obscure clinical signs of cardiac arrest, clinicians should palpate peripheral pulses immediately after endotracheal intubation if continuous arterial and capnography waveforms are unavailable. The risk of arrest in severely hypovolemic patients is particularly high if the preintubation systolic blood pressure is >90 mm Hg (1, 2, 39). However, blood pressure and other clinical signs may be normal despite severe hypovolemia, and clinicians should be prepared for hemodynamic deterioration whenever there has been significant blood loss. The shock

index (heart rate divided by systolic blood pressure) may be more sensitive than other clinical findings for identifying severe hypovolemia (47).

In general, lower doses of sedatives should be used for endotracheal intubation in patients with severe hemorrhage. Theoretically, propofol causes more circulatory depression than etomidate or ketamine. However, all sedatives and analgesics can cause hypotension in patients with severe hemorrhage (1, 38, 39, 48). Sedatives and neuromuscular blocking agents stop spontaneous negative pressure inspirations and therefore may contribute to hypotension. In certain situations, maintaining spontaneous efforts during intubation may blunt hemodynamic deterioration (39).

Severe hemorrhage accelerates desaturation during apnea. Significant loss of red blood cell mass depletes the largest O_2 reservoir in the body. Therefore, clinicians should anticipate rapid desaturation during apnea even if patients have a normal O_2 saturation before induction of anesthesia. This complication is more common with hemorrhage than with simple hypovolemia. In addition to adequate preoxygenation, red blood cell transfusion before neuromuscular blockade can prolong time to desaturation. Transfusion is more effective than crystalloid resuscitation in delaying desaturation (49). Apneic oxygenation also may prevent desaturation during rapid sequence induction of anesthesia (50).

Mechanical Ventilation during Hemorrhagic Shock

A priority for mechanical ventilation during severe hemorrhage is to maintain venous return by using the lowest mean airway pressure. A reasonable approach is to set PEEP and respiratory frequency as low as possible. PEEP can be briefly set to 0 cm H_2O during hemodynamic crises. To limit plateau pressure to 30 cm H_2O, an initial tidal volume of 8 ml/kg of ideal body weight is reasonable. If the patient has hypercapnia and acidemia, the respiratory rate can be carefully increased. In the absence of lung disease, an arterial CO_2 more than 5 mm Hg higher than the end-tidal CO_2 can help identify patients with increased dead space due to hemorrhagic shock (12, 13). In this situation, increasing respiratory rate and tidal volume can worsen shock and fail to reduce Pa_{CO_2}. Therefore, fluid or blood product resuscitation may be more effective than increasing minute ventilation for hypercapnia. Similarly, clinicians should be cautious about increasing minute ventilation to compensate for metabolic acidosis that is due to hypoperfusion.

The low PEEP approach may be harmful in patients at risk for lung derecruitment when the patient is sedated and supine. Examples include patients with severe acute lung injury, such as from large-volume aspiration. Patients with severe central adiposity are also at risk for atelectasis with low PEEP. Therefore, clinicians may need to administer additional resuscitation fluid as they carefully increase PEEP.

Table 2. Management of respiratory failure during hemorrhagic shock

Relieve obstructed airway
Provide rescue breaths for apnea or agonal respiration
Use lowest possible mean airway pressure during mechanical ventilation
Reduce dose of induction agent for endotracheal intubation
Monitor end-tidal CO_2 to detect decrease in cardiac output

Definition of abbreviations: CO_2 = carbon dioxide.

During hemorrhagic shock, patients' spontaneous efforts while on mechanical ventilation may blunt some of the deleterious effects of positive pressure. However excessive respiratory efforts may be a sign of dyspnea and contribute to acute lung injury and the metabolic production of CO_2. Clinicians should balance these concerns when targeting the depth of sedation (51, 52).

Alternative Strategies

Impedance threshold and negative pressure devices can lower intrathoracic pressure and improve venous return. However, there is no good evidence supporting their routine use in hemorrhagic shock (53).

Conclusions

To manage respiratory failure due to hemorrhagic shock, clinicians should prioritize airway patency and use the minimum possible mean airway pressure during assisted or mechanical ventilation. Clinicians should also recognize that hypoperfusion worsens dead space fraction (Table 2). ■

Author disclosures are available with the text of this article at www.atsjournals.org.

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